Short Communication: Temperature Profiles in Wood Members Exposed to Fire

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INTRODUCTION

Part 1.2 of Eurocode 5 was recently published as a voluntary European standard (ENV).[1] Eurocode 5 deals with timber construction. Part 1.2 covers structural fire design, and includes three methods for calculating the fire endurance of exposed wood members under standard fire conditions.

The first two methods are simple calculation procedures which determine the time to failure when the remaining cross-section of wood ceases to sustain the imposed load. The remaining cross-section is determined on the basis of empirical charring rates. The first method uses cold strength and stiffness values, but increases the char depth by 7 mm to account for strength loss in a narrow heated zone ahead of the char front. The second method does not increase char depth, but slightly reduces strength and stiffness values of the remaining cross-section to account for the same phenomenon. These reductions are a function of the ratio of the perimeter to the area of the remaining cross-section.

The third method is not described in detail in the Eurocode, but is an option to use more accurate and sophisticated computer design methods with finite element methods as the primary example. To avoid the need for a detailed heat transfer calculation, Annex E recommends generic temperature profiles. These profiles specify the temperature as a function of distance from the char front, x. It is assumed the temperature at the char front, T_p, is equal to 300°C. This temperature is close to the value of 550°F (288°C) commonly accepted in North America. The following generic temperature profile is given for when the member behaves as a semi-infinite solid:

$$T = T_i + (T_p - T_i)\left(1 - \frac{x}{a}\right)^2 \qquad (1)$$

where

T = temperature (°C),

T_i = initial temperature (°C),

T_p = char front temperature (300°C),

x = distance from the char front (mm),

a = thermal penetration depth (40 mm).

A similar equation with an exponential term in place of a power term was reported by Schaffer.[2] Equation (1)

is based primarily on German measurements of temperature profiles of wood slabs and beams exposed in a furnace according to the ISO 834 standard temperature-time curve.

Extensive charring rate experiments were conducted by White in the 1980s. In this short communication, White's measurements are used to verify the Eurocode recommended temperature profile. White performed his experiments according to ASTM E119. The exposure and test conditions prescribed by this standard are slightly different from those in European fire resistance test standards based on ISO 834. However, numerous studies have shown that the performance of exposed wood members is comparable, regardless of whether the test is conducted according to ASTM El 19 or ISO 834. Hence, it is appropriate to use White's ASTM El 19 data in an attempt to verify temperature profiles based on German test results.

Eurocode 5, Part 1.2 includes a second equation for use when the member no longer behaves as a semi-infinite solid. This equation is useful for members which are exposed on two opposite sides. The second equation could not be checked since White's data were obtained for slabs exposed to fire on one side only.

WHITE'S DATA

As part of his PhD study, Robert White tested slabs of eight different wood species in a furnace according to the standard ASTM fire endurance test method E-119.[3,4] The species that were tested are given in Table 1. They were selected on the basis of a 2^3 factorial design,

Table 1. Wood species tested by White

Common name	Botanical name	Dry density, ρ_o (kg m^{-3})
Spruce	*Picea engelmannii*	425 ± 6
Western redcedar	*Thuja plicata*	310 ± 19
Southern pine	*Pinus* sp.	510 ± 94
Redwood	*Sequoia sempervirens*	345 ± 41
Hard maple	*Acer* sp.	690 ± 57
Yellow poplar	*Liriodendron tulipifera*	505 ± 10
Red oak	*Quercus* sp.	665 ± 84
Basswood	*Tilia* sp.	400 ± 22

maximizing the relative effects of density, permeability and chemical composition.

Test specimens measured 230 mm × 510 mm with a thickness of 63 mm. Several thermocouples were embedded into the specimens, to measure temperature at 13,25, 38 and 51 mm from the exposed surface. Tests were conducted after conditioning of specimens to equilibrium at 30%, 50%, 65% and 80% relative humidity and a temperature of 23-27°C.
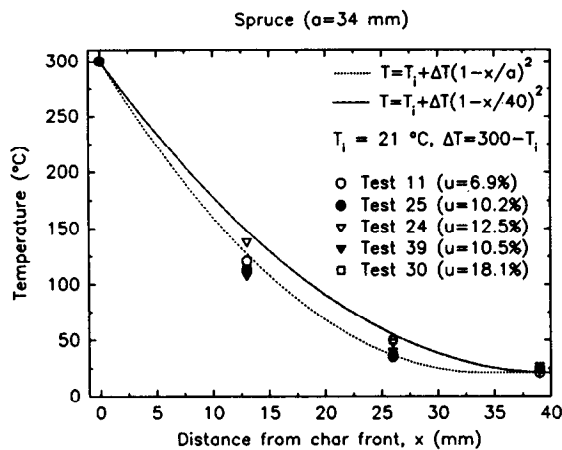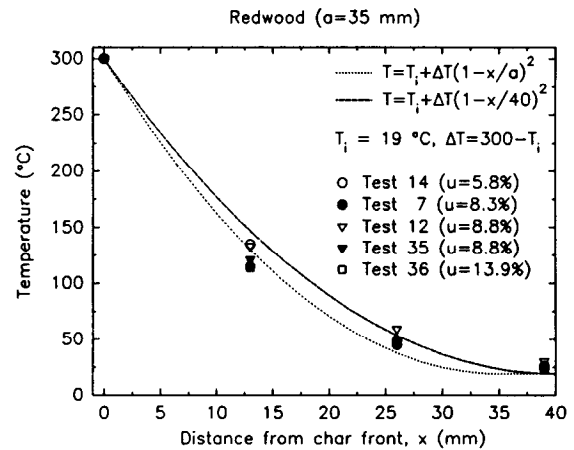

Figure 1. Temperature measurements and profiles for spruce.

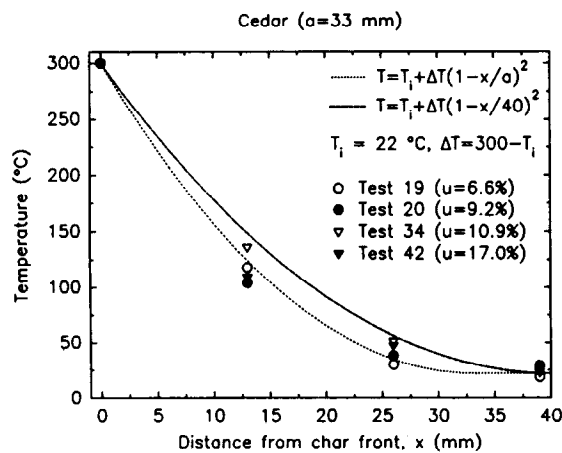**Figure 2.** Temperature measurements and profiles for cedar.

Figure 3. Temperature measurements and profiles for pine.

Figure 4. Temperature measurements and profiles for redwood.

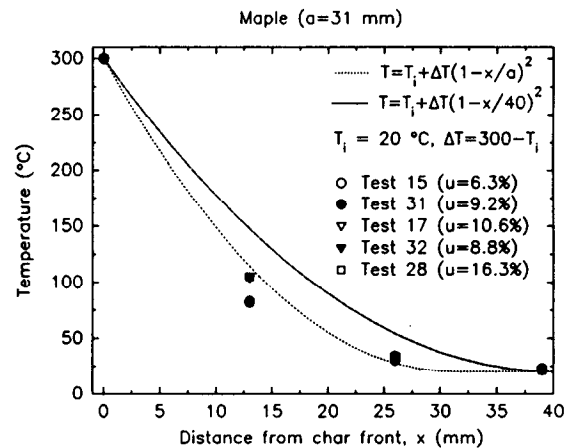**Figure 5.** Temperature measurements and profiles for maple.

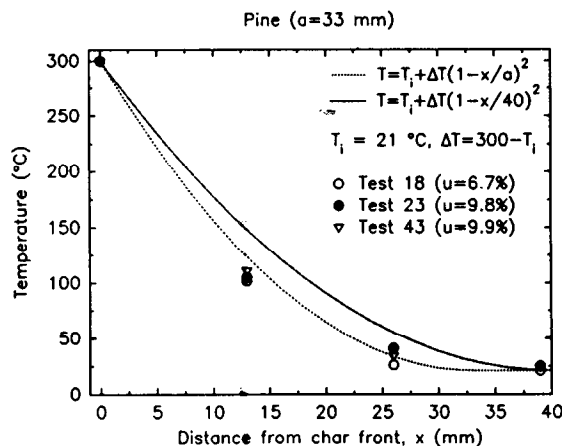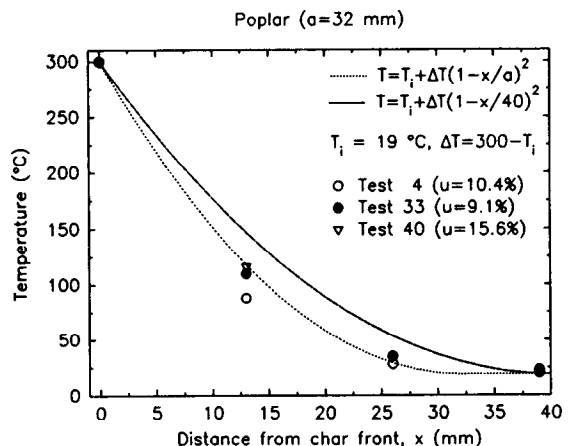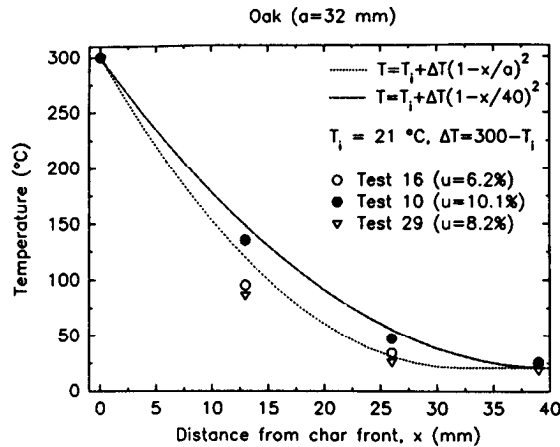**Figure 6.** Temperature measurements and profiles for poplar.

Oak (a=32 mm)

Figure 7. Temperature measurements and profiles for oak.
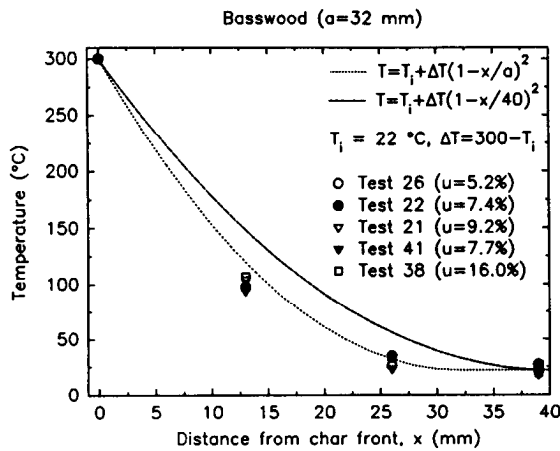
Basswood (a=32 mm)

Figure 8. Temperature measurements and profiles for basswood.

The measured temperatures at the time when the thermocouple at 13 mm from the exposed surface reads 300°C are shown in Figs 1-8. Non-linear regression analyses were performed to fit eqn. (1) to the measured temperatures. The values for the penetration depth, a, that result in the best fit are listed in Table 2. The

Table 2. Best-fit values for penetration depth, a

Common name	Best-fit a (mm)
Spruce	34
Western redcedar	33
Southern pine	33
Redwood	35
Hard maple	31
Yellow poplar	32
Red oak	32
Basswood	32

resulting temperature profiles, together with the recommended Eurocode profile, are shown in the figures. For each of the tests, moisture content u of the specimen is also shown in the figures. The measured temperature profiles do not appear to be very sensitive to moisture content. In almost every case, $a = 40$ mm results in conservative (slightly higher) calculated temperatures. However, the differences are minor, and the profile recommended in the Eurocode is quite reasonable. A closer look at the figures indicates that for hardwoods (the bottom four species in Table 1), thermal penetration depth a can perhaps be reduced to 35 mm.

CONCLUSIONS

Temperature measurements made by White on slabs of eight wood species with a range of moisture contents exposed to ASTM E119 are quite consistent with a generic profile recommended in Eurocode 5, Part 1.2. The temperature profiles appear to be insensitive to moisture content of the specimens. The thermal penetration depth $a = 40$ mm proposed in the Eurocode generally yields slightly more conservative (higher) temperatures than those measured by White. White's data indicate that a can perhaps be reduced to 35 mm for hardwoods.

REFERENCES

1. Eurocode 5, Part 1.2, Structural Fire Design, CEN, Brussels (1993).
2. E. L. Schaffer, Structural fire design: wood FPL Research Paper 450, US Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI (1984).
3. R. H. White, *Charring Rates of Different Wood Species*, PhD Thesis, University of Wisconsin, Madison (1988).
4. R. H. White and E. V. Nordheim, Charring rate of wood for ASTM E119 Exposure *Fire Technology* **28**, 5–30 (1992).